FILLING-IN OF FAR-RED AND NEAR-INFRARED SOLAR LINES BY TERRESTRIAL AND ATMOSPHERIC EFFECTS: SIMULATIONS AND SPACE-BASED OBSERVATIONS FROM SCIAMACHY AND GOSAT

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1 Introduction

Mapping of terrestrial vegetation fluorescence from space is of interest because it can potentially provide global information on the functional status of vegetation including light use efficiency and global primary productivity that can be used for global carbon cycle modeling. Space-based measurement of solar-induced chlorophyll fluorescence is challenging, because its signal is small as compared with the much larger reflectance signal. Ground- and aircraft-based approaches have made use of the dark and spectrally-wide O_2-A (~760 nm) and O_2-B (~690 nm) atmospheric features to detect the weak fluorescence signal [1]. More recently, Joiner et al. [2] and Frankenberg et al. [3] focused on longer-wavelength solar Fraunhofer lines that can be observed with space-based instruments such as the currently operational GOSAT. They showed that fluorescence can be detected using Fraunhofer lines away from the far-red chlorophyll-a fluorescence peak even when the surface is relatively bright.

Here, we build on that work by developing methodology to correct for instrumental artifacts that produce false filling-in signals that can bias fluorescence retrievals. We also examine other potential sources of filling-in at far-red and NIR wavelengths. Another objective is to explore the possibility of making fluorescence measurements from space with lower spectral resolution instrumentation than the GOSAT interferometer.

We focus on the 866 nm Ca II solar Fraunhofer line. Very few laboratory and ground-based measurements of vegetation fluorescence have been reported at wavelengths longer than 800 nm. Some results of fluorescence measurements of corn leaves acquired in the laboratory using polychromatic excitation at wavelengths shorter than 665 nm show that at 866 nm, the measured signal is of the order of 0.1–0.2 $\mathrm{mW\,m^{-2}\,nm^{-1}\,sr^{-1}}$ [4].

In this work, we use the following satellite observations: We use SCIAMACHY channel 5 in nadir

mode that covers wavelengths between 773 and 1063 nm at a spectral resolution of 0.54 nm. GOSAT has two instrument packages: the Thermal And Near-infrared Sensor for carbon Observation-Fourier Transform Spectrometer (TANSO-FTS) and the Cloud and Aerosol Imager (CAI). We use TANSO-FTS band 1, which extends from approximately 758 to 775 nm and we use cloud fraction derived from the CAI. We compare satellite-derived fluorescence with the Enhanced Vegetation Index (EVI), an Aqua/MODIS-derived vegetation reflectance-based index that indicates relative greenness and is used to infer photosynthetic function.

2 Simulated filling-in at 866 nm

We simulated the effects of additive signals such as fluorescence, fire, and volcanoes as well as effects of rotational- and vibration-Raman scattering on space-based observations of the Ca II line near 866 nm with several different spectral resolutions. The filling-in due to an additive signal of $0.2\,\mathrm{mW\,m^{-2}\,sr^{-1}\,nm^{-1}}$ at SCIAMACHY resolution is small (<1 %), but observable if systematic effects can be accounted for.

We computed the filling-in of the 866 nm Ca II line due to rotational-Raman scattering (RRS) using the LIDORT-RRS code of [5]. The filling-in owing to RRS is about a factor of 6 less than that due to an additive signal of $0.2\,\mathrm{mW\,m^{-2}\,sr^{-1}\,nm^{-1}}$. We also assessed the vibrational Raman scattering (VRS) contribution using the single scattering approximation and found that for typical values of surface albedo over land (>0.2), the filling-in is negligible.

3 Retrieval methodology

We use the same GOSAT fitting window as [2] (769.90–770.25 nm). We have a second fitting window between 758.45 and 758.85 nm, similar to that used by [3]. We scale the results from the 758 nm window by 0.696 and add them those from the 770 nm window to increase the signal-to-noise ratio (SNR) of the combined additive signal. We also derive an additive signal using the 866 nm Ca II solar line from SCIAMACHY with the spectral band 863.5–868.5 nm.

We use the following simplified model for the observed Earth spectral radiance $\vec{I}(\lambda)$ that assumes negligible atmospheric absorption and scattering:

$$\vec{I}(\lambda) = K\vec{E}(\lambda)^{*} + \overline{F}, \tag{1}$$

where $\vec{E}(\lambda)^{*}$ is a reference spectrum ideally containing no filling-in from the source of interest (fluorescence) [2]. The main difference between our approach and that of [2] is that we use spectral

radiance measurements made over the cloudy ocean as a reference rather than a measured or computed solar irradiance spectrum. There are several advantages of using cloudy Earth radiance spectra as a reference to derive a terrestrial additive signal as opposed to solar irradiance spectra (measured or computed) as detailed in [4].

When comparing the derived additive signals with vegetation indices, we use a quantity called "scaled-F" [2], defined as the retrieved $\overline{F}$ divided by cos(SZA). This scaling roughly accounts for variations in $\overline{F}$ due to the incoming (clear-sky) PAR.

4 Results and discussion

Figure 1 shows retrieved gridded monthly mean scaled-F for July and December 2009 derived from GOSAT and SCIAMACHY. The values from SCIAMACHY at 866 nm are significantly smaller than those at 770 nm, as would be expected if the signals originate from chlorophyll-a fluorescence associated with the declining emission tail throughout the NIR region. Similar seasonal variation in scaled-F is seen by both sensors as well as EVI. These variations in GOSAT and SCIAMACHY scaled-F are consistent with a vegetation source such as fluorescence. Like the EVI, a retrieved fluorescence signal (scaled by incoming PAR) is sensitive to the amount of green biomass contained within the sensor field-of-view or fractional amount of intercepted PAR.

We note a significant filling-in (retrieved as $\overline{F}$) at 866 nm over parts of the Sahara desert and the Saudi Arabian peninsula where vegetation is sparse. Filling-in over barren regions may be produced by luminescent minerals in soil and/or rock.

5 Conclusions

Our simulations indicate that terrestrial fluorescence filling-in of the 866 nm Ca II line can be detected using hyperspectral instruments (spectral resolutions of the order of tenths of a nm) such as SCIAMACHY if the fluorescence at this wavelength is of the order of 0.1–0.2 $\mathrm{mW\,m^{-2}\,nm^{-1}\,sr^{-1}}$. After corrections for instrumental artifacts, we retrieved an additive signal over land at 866 nm with SCIAMACHY. The magnitude of the derived additive signal at 866 nm is similar to that of our laboratory measurements. The spatial and temporal patterns of the detected additive signals at 866 nm are consistent with a vegetation source; they are similar to those of EVI and those derived from additive signals at 770 and 758 nm where fluorescence from chlorophyll-a in vegetation is stronger and expected to be the primary source of the signals.

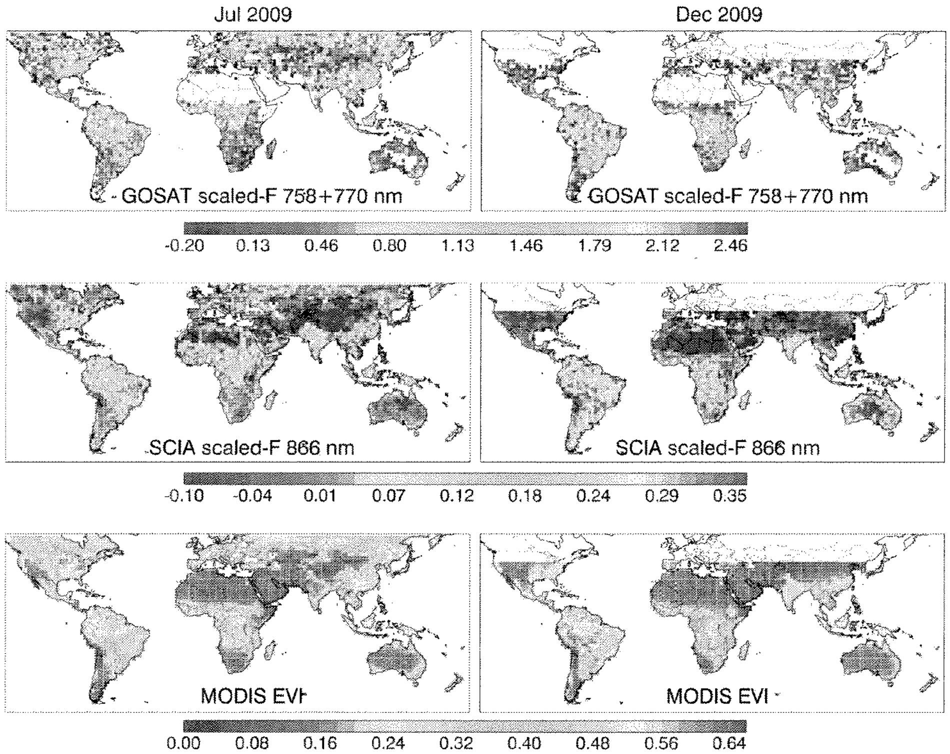

Figure 1: *Derived monthly averages for July (left panels) and December (right panels) 2009; Top: scaled-F (unitless) from GOSAT (0.696*758 nm + 770 nm); Middle: scaled-F from SCIAMACHY (866 nm); Bottom: Aqua MODIS enhanced vegetation index (EVI)*

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